REVIEW AND DESIGN OF PRINTED REFLECTARRAY ANTENNAS

John Huang

Jet propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109, USA

Abstract: A printed reflectarray is an antenna similar to a parabolic reflector, but with its reflecting surface capable of being designed either flat or slightly curved for conformal mounting onto an existing structure without adding significant amount of mass and volume to the structure. For large deployable apertures, the antenna's reflecting surface, being flat, can be more easily and reliably deployed than a curved parabolic reflector. In addition, the main beam of the antenna can be designed to tilt or actively scanned to large angles from the broadside direction. This article gives a brief review of the development history and a design methodology for printed reflectarray antennas. A few recent developments, such as a Ka-band microstrip reflectarray and an X-band inflatable reflectarray, are also presented.

Introduction: The printed reflectarray antenna consists of a very thin and flat (can be slightly curved) reflecting surface and an illuminating feed, as shown in Figure 1. On the reflecting surface, there are many isolated elements (e.g. printed patches, dipoles or rings) without any power division network. The feed antenna illuminates these microstrip elements which are designed to scatter the incident field with phases that are required to form a planar phase front. This operation is similar in concept to the use of a parabolic reflector that naturally scatters a planar phase front when a feed is placed at its focus. Thus the term "flat reflector" is sometimes used to describe the printed reflectarray. There are several methods for reflectarray elements to achieve a planar phase front. One is to use identical microstrip patches with different-length phase delay lines attached so that they can compensate for the phase delays over the different paths from the illuminating feed. The other is to use variable-size patches, dipoles or rings so that elements can have different scattering impedances and, thus, phases to compensate for the different feed-path delays. The third method, for circular polarization only, has all identical circularly polarized elements but with different angular rotations to compensate for the feed path length differences.

The low-profile printed microstrip reflectarray combines some of the best features of the microstrip array technology and the traditional parabolic reflector antenna. Similar to a parabolic reflector, the reflectarray can achieve very good efficiency (> 50%) for very large aperture since no power divider is needed here and thus very little insertion loss is encountered. On the other hand, very similar to an array antenna, the reflectarray can have its main beam designed to tilt at a large angle (> 50 deg) from its broadside direction. Electronic phase shifters can be implanted into the elements for electronic beam scanning. For circular polarization, a micro-machined miniature motor can be placed under each element to mechanically rotate the element and thus allow the array's main beam to scan. With these beam-scanning methods of the reflectarray, the complicated beamforming network and high-cost T/R modules of a conventional phased array are no longer needed. When a large aperture antenna requires a deployment mechanism, the flat structure of the reflectarray allows a much simpler and reliable folding or inflation mechanism than the curved surface of a parabolic reflector. The reflectarray, being in the form of a printed microstrip antenna, can be fabricated with a simple and low-cost etching process, especially when produced in large quantities. With all the above advantages, there is one distinct disadvantage associated with the printed reflectarray. This is its inherent narrow bandwidth which generally cannot exceed ten percent. This bandwidth behavior will be discussed further in a later section.

Review of Historical Developments: The reflectarray antenna concept, shown in Figure 1, was first demonstrated during the early 1960s [1]. Large open-ended waveguide elements were used at relatively low microwave frequencies, which resulted in very bulky and heavy antennas. In addition, the efficiencies of these reflectarrays were not studied and optimized. More than ten years later (in the mid 1970's), the very clever concept of spiraphase reflectarray was developed [2]. Switching diodes were used in an 8-arm spiral element of a circularly polarized reflectarray to electronically scan the main beam to large angles from the broadside direction. Due to the thick spiral cavity and large electronic components, the overall spiraphase reflectarray was relatively bulky and heavy. Its efficiency also remained to be improved. It should be noted here that, in order to improve the efficiency, the intricate relations between the element beamwidth, element spacing, and f/D (focal length / diameter) ratio must be well designed; otherwise, a large backscattered component field or a mismatched surface impedance would form.

Due to the invention of the low-profile microstrip antennas, various printed microstrip reflectarray antennas were developed in the late 80's and early 90's. They came in various forms, but all with flat low-profile and low-mass reflecting surfaces. The ones that used identical patch elements with different-length phase delay lines [3,4,5,6,7] have some of their elements depicted in Figure 2(a). The phase delay lines, having lengths half-wavelength long or shorter, are used to compensate the different path lengths from the illuminating feed. This can also be accomplished by using elements made of printed dipoles with variable dipole sizes [8], as shown in Figure 2(b). Different dipole sizes will yield different scattering impedances which then provide the different phases to compensate for the different path-length delays. Similarly, microstrip patches with variable patch sizes [9], shown in Figure 2(c), were developed. Printed dipole elements were also used to form a frequency scanned grating-reflector antenna [10]. Printed annular rings of variable sizes arranged in Fresnel Zone configuration were used to focus the beam [11]. Circularly polarized microstrip patches with identical size but variable angular rotations [12], as shown in Figure 2(d), were designed to form a highly-efficient high-performance reflectarray. In the 1996 Phased Array Conference, a 94 GHz monolithic reflectarray [13], using 1-bit PIN diode phase shifters, was reported to achieve wide-angle (± 45°) electronic beam scanning. In the same conference, a 35 GHz reflectarray, using waveguide/dielectric elements with 3-bit ferrite phase shifters [14], was also reported to achieve ± 25-deg beam scanning. From all the above developments, it can be seen that the reflectarray antenna technology is becoming very mature and has a variety of applications throughout the microwave and millimeter-wave spectra.

Design of Reflectarray: The design and analysis of the reflectarray can be achieved through conventional array theory for arbitrarily located feed and arbitrary main beam direction, as given in references 4 and 17, where no mutual coupling effect is included. To include mutual coupling, FDTD analysis on subarray of a few elements was carried out in reference [7] or infinite array theory was employed in reference [15]. Both approaches have some degree of approximation and they require tremendous amounts of calculation time for relatively large aperture with several thousands of elements or more. Fortunately, the mutual coupling effect has not proven to be significant in an ordinary microstrip reflectarray and, thus, the conventional array theory can be used to perform design and most of the analysis tasks. The following gives a very simple method to calculate the compensating phase delay needed for each element of a reflectarray with a broadside directed beam. The differential path length for each element is given as:

$$\Delta L_{m,n} = L_{m,n} - L_{0,0} \ , \qquad (1)$$

where $L_{m,n}$ is the distance between the feed and the mnth element, which can be obtained using simple geometry. $L_{0,0}$ is the distance between the feed and the center of the reflectarray surface. $\Delta L_{m,n}$ is thus the differential feed path length for the mnth element. To achieve a collimated radiation, the phase advancement $\Delta\phi_{mn}$ needed for the mnth element is given by

$$\Delta\phi_{mn} \text{ in degrees} = [\ \Delta L_{m,n} / \lambda_0 - \text{integer of} (\ \Delta L_{m,n} / \lambda_0\ )] \times 360 \ , \qquad (2)$$

For a reflectarray using identical patches but different microstrip delay lines, the length of the mnth delay line needs to be shorter than the center element delay line by Δd_{mn}, where

$$\Delta d_{mn} = \lambda_g \times \Delta\phi_{mn} / 360 / 2, \qquad (3)$$

λ_g is the guided wavelength of the microstrip transmission line. The delay line of the center element should be set at maximum length of λ_g / 2 or slightly longer. The width of the line should be such that the line impedance is matched to the patch resonator. Often a matched line requires the line to be too thin to achieve a reasonable etching tolerance. In this case, perfect impedance match is not necessary. However, at least a –10 dB return loss should be required for the line impedance match to the patch.

Other important factors that need to be considered in the design of a reflectarray are aperture efficiency, bandwidth, and beam-pattern performance. The aperture efficiency (η_a) can be defined as the product of the illumination (η_i) and spillover (η_s) efficiencies:

$$\eta_a = \eta_i \times \eta_s \qquad (4)$$

In reference [16], the illumination efficiency is obtained in closed form as

$$\eta_i = \frac{\left[\left(\left(1+\cos^{q+1}\theta_e\right)/(q+1)\right)+\left(\left(1-\cos^{q}\theta_e\right)/q\right)\right]^2}{2\tan^2\theta_e\left[\left(1-\cos^{2q+1}\theta_e\right)/(2q+1)\right]}$$

and the spillover efficiency is given by

$$\eta_s = 1 - \cos^{2q+1}\theta_e$$

where q is the exponent of the feed pattern function $\cos^q\theta$ and θ_e is half the subtend angle from the feed to the reflectarray aperture. As an example, Figure 3 gives the calculated curve of spillover and illumination efficiencies versus the feed pattern factor q for a half-meter 32 GHz reflectarray with an f/D ratio of 1.0 ($\theta_e = 26.6°$). It shows that a maximum aperture efficiency is achieved at q = 10.5. Figure 4 shows aperture efficiency as a function of f/D ratio for the same half-meter 32 GHz reflectarray with a feed q factor of 8. The maximum aperture efficiency is achieved, in this case, with an f/D ratio of 0.87. It can be seen that equations similar to (5) and (6) are essential in obtaining an optimum efficiency design.

The bandwidth of a microstrip reflectarray is another important factor to be considered in practice and is limited by four factors [17]: (1) the microstrip element, (2) the array element spacing, (3) the feed antenna bandwidth, and (4) the differential spatial phase delay. The fourth factor, differential spatial phase delay, is generally the most governing one in determining the bandwidth of a reflectarray. With the effects of the above factors (2) and (4) included, the directivity is calculated versus frequency, as shown in Figure 5, for a half-meter 32 GHz reflectarray. Two curves are plotted in this figure; one has an f/D ratio of 1.0 and the other is 0.5. It is obvious that the reflectarray with a larger f/D ratio will yield a wider bandwidth. The pattern shape is also important in designing an optimum reflectarray. Figures 6 and 7 present the patterns for the same reflectarray with f/D ratios of 0.5 and 1.0, respectively. Again, larger f/D ratio shows better pattern performance in terms of sidelobe level and directivity.

Recent Developments: Two microstrip reflectarrays recently developed by the author will be presented in the symposium. One is a circularly polarized 32 GHz reflectarray with a half-meter diameter and variably rotated elements [12]. This antenna, shown in Figure 8, achieved sidelobe and cross-pol levels below –30 dB level and a peak efficiency of more than 60%. The second antenna is a one-meter inflatable X-band microstrip reflectarray, shown in Figure 9, which achieved a mass of 1.2 kg.

Acknowledgment: The research activities described in this article were carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Review and edit of this article by Dr. Aluizio Prata, Jr. is deeply appreciated.

References:

1. D.G. Berry, R.G. Malech, and W.A. Kennedy, "The reflectarray antenna", IEEE Trans. Antennas Propagat., vol. AP-11, Nov. 1963, pp.645-651.

2. H.R. Phelan, "Spiraphase reflectarray for multitarget radar", Microwave Journal, vol. 20, July 1977, pp. 67-73.

3. R.E. Munson and H. Haddad, "Microstrip reflectarray for satellite communication and RCS enhancement and reduction", U.S. patent 4,684,952, Washington, D.C., August 1987.

4. J. Huang, "Microstrip reflectarray antenna for the SCANSCAT radar application", Jet Propulsion laboratory report no. 90-45, Nov. 1990.

5. D.C. Chang and M.C. Huang, "Multiple polarization microstrip reflectarray antenna with high efficiency and low cross-polarization", IEEE Trans. Antennas Propagat., vol. 43, Aug. 1995, pp. 829-834.

6. R.D. Javor, X.D. Wu, and K. Chang, "Beam steering of a microstrip flat reflectarray antenna", in IEEE AP-S/URSI Symp., June 1994, pp. 956-959.

7. Y. Zhang, K.L. Wu, C. Wu, and J. Litva, "Microstrip reflectarray: full-wave analysis and design scheme", IEEE AP-S/URSI Symposium, June 1993, pp. 1386-1389.

8. A. Kelkar, "FLAPS: Conformal phased reflecting surfaces", Proc. IEEE National Radar Conf., Los Angeles, CA, March 1991, pp. 58-62.

9. S.D. Targonski and D.M. Pozar, "Analysis and Design of a microstrip reflectarray using patches of variable size", IEEE AP-S/URSI Symposium, June 1994, pp. 1820-1823.

10. F.S. Johansson, "A new planar grating-reflector antenna", IEEE Trans. Antennas Propagat., vol. 38, Sept.1990, pp. 1491-1495.

11. Y.T. Guo and S.K. Barton, "Phase correcting zonal reflector incorporating rings", IEEE Trans. Antennas propagat., vol. 43, April 1995, pp. 350-355.

12. J. Huang and R.J. Pogorzelski, "A Ka-band microstrip reflectarray with elements having variable rotation angles", IEEE Trans. Antennas Propagat., vol. 46, May 1998, pp. 650-656.

13. J.M. Colin, "Phased array radars in France: present and future", IEEE Symp. on Phased Array System and Technology, Boston, MA, Oct. 1996, pp. 458-462.

14. A.A. Tolkachev, V.V. Denisenko, A.V. Shishlov, and A.G. Shubov, "High-gain antenna system for millimeter wave radars with combined electrical and mechanical beam steering", IEEE Symp. on Phased Array System and Technology, Boston, MA, Oct. 1996, pp. 266-271.

15. D.M. Pozar and T.A. Metzler, "Analysis of a reflectarray antenna using microstrip patches of variable size", Electronics Letters, April 1993, pp. 657-658.

16. J. Huang, "Analysis of a microstrip reflectarray antenna for microspacecraft application", JPL TDA progress report 42-120, Feb. 1995, pp. 153-173.

17. J. Huang, "Bandwidth study of microstrip reflectarray and a novel phased reflectarray concept", IEEE AP-S/URSI Symposium, June 1995, pp. 582-585.

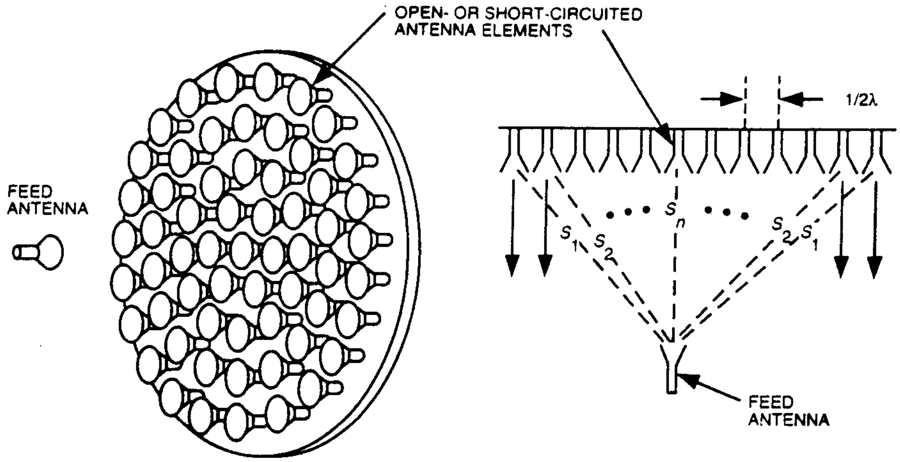

Figure 1. Configuration of a reflectarray antenna.

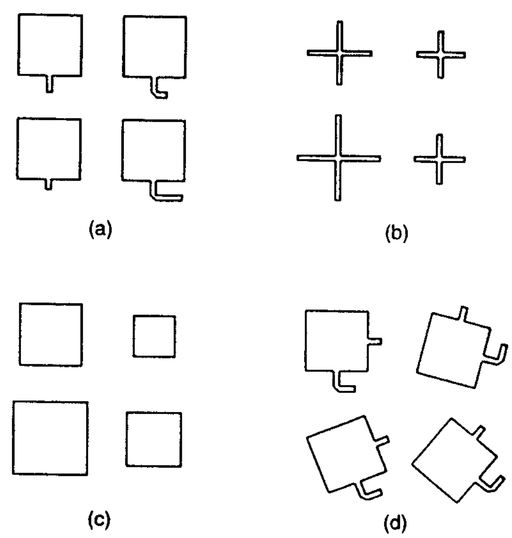

Figure 2. Various printed reflectarray elements, (a) identical patches with variable-length phase delay lines, (b) variable-size dipoles, (c) variable-size patches, (d) variable angular rotations.

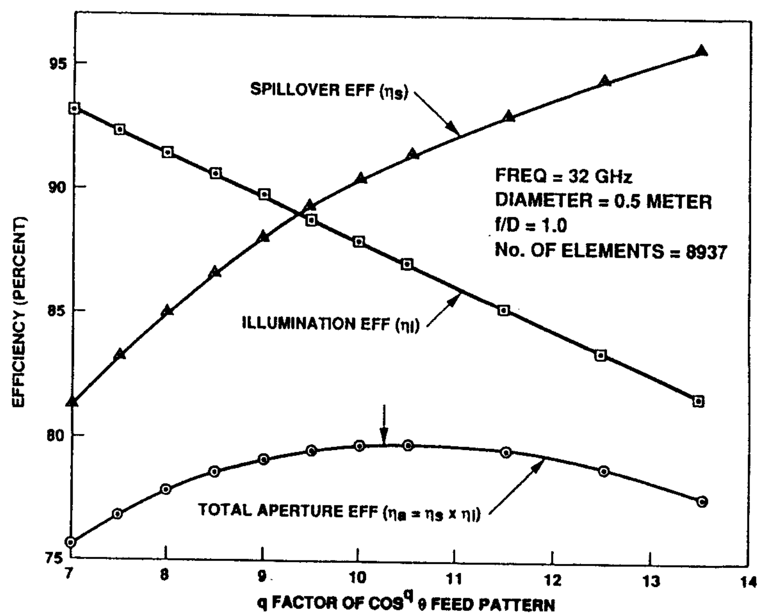

Figure 3. Spillover and illumination efficiencies versus feed pattern shape.

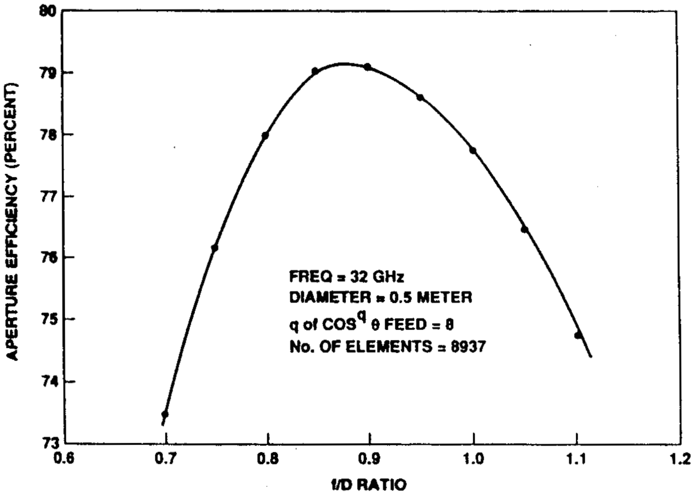

Figure 4. Aperture efficiency versus f/D ratio.

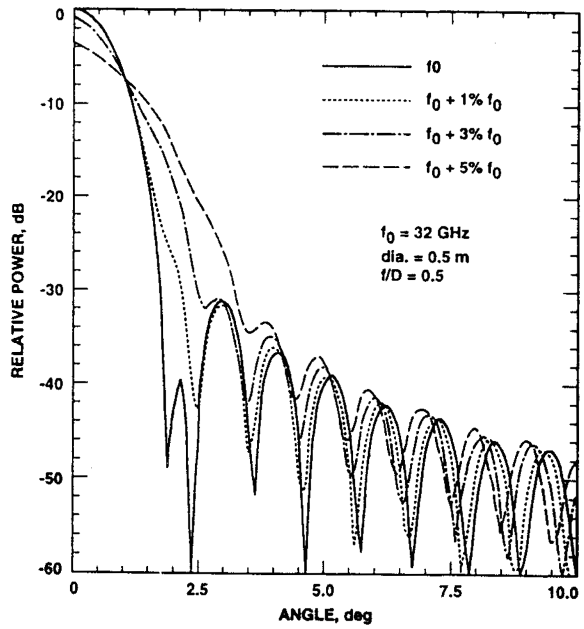

Figure 6. Calculated radiation patterns for various frequency deviations, f/D=0.5.

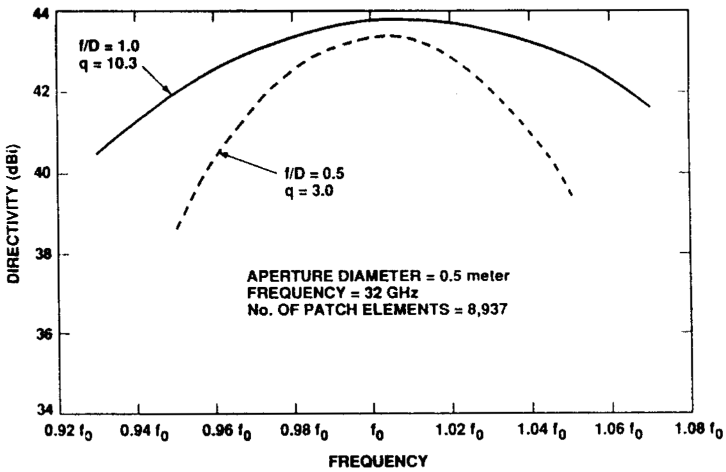

Figure 5. Reflectarray directivity versus frequency.

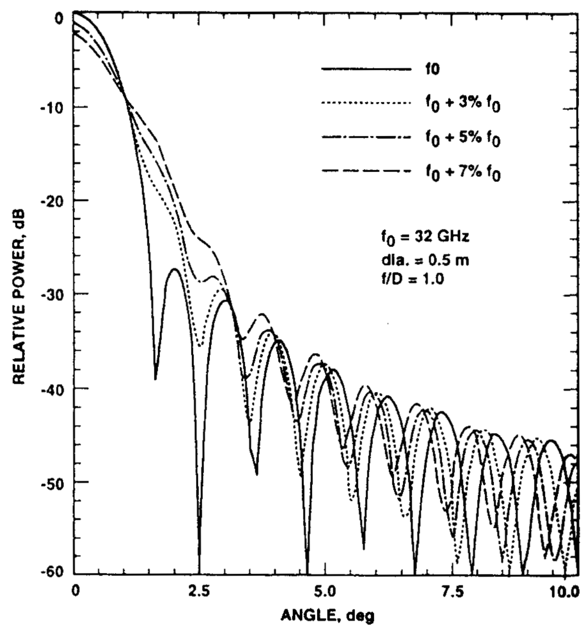

Figure 7. Calculated radiation patterns for various frequency deviations, f/D=1.0.

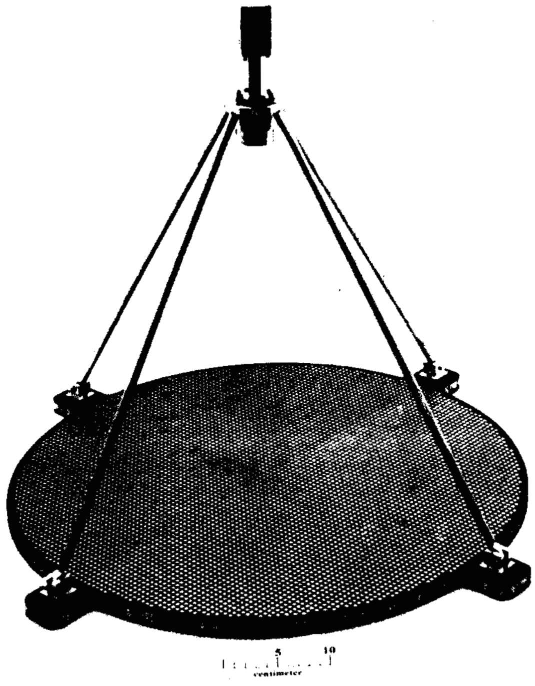

Figure 8. Photo of a 0.5m 32 GHz CP microstrip reflectarray.

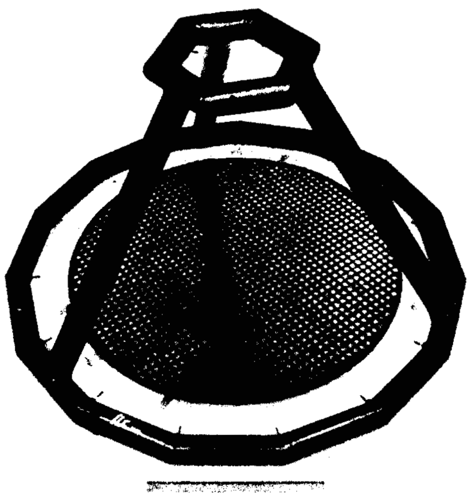

Figure 9. Photo of a 1.0m X-band CP inflatable microstrip reflectarray.